Modelling and Evaluation of the motive and hydrodynamic performance of Cargo Vessels with green hydrogen and synthetic fuels

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December 2023

Abstract –**Similar to other industries, maritime industry also facing increasing restrictions imposed on ships regarding pollution control. This is driving the search of alternative fuels. This study aims in studying these fuels with focus on hydrogen for a particular ship, ALMADENSE operating on Tagus River in Lisbon region of Portugal. Dynamic forces acting on the ship has been studied for a year and results are compared with possible cases. These cases are, 1st: business as usual (diesel engine), 2nd replacing of diesel engine with hydrogen hybrid system and, 3rd replacement of current ship with new hydrogen hybrid ship. The study is based on numerical calculation and simulating them in SIMULINK.**

As the result, 2nd case suites best in both the fronts namely, environmental, and economic. A 370kWh battery with 7 modules of 200kW each is suggested for the studied case.

I. INTRODUCTION

It is estimated that around 80-90% of world trade is done ships[1], main reason behind this being its relatively low transportation cost. There is a direct relation between world trade and world economic growth[2][3] therefore, with the increasing world economy and shipping industry, carbon emission is also expected to swell if the business as usual continues. To address this challenge, IMO has made several efforts to control these emissions by formulating emission related policies and regulations. There are a range of measures that an operator could adapt to achieve these reductions like regulatory requirements (EEDI, SEEMP, etc.), advancements in technology (improved engines, alternative fuels, etc.), adjustments related to ship's operation (slow steaming, low emission fuels, etc.), and market-based instruments (cap-and-trade systems, rebate mechanism, etc.) [4]. On top of IMO's regulations, local governments are also actively taking part in policy making. The recent example of such policy is an agreement related to Emission Trading Systems (EU ETS) made by EU's legislative bodies in January 2023 to be enforced in January 2024 which penalize the ship operators on the amount of carbon emitted.

It is clear that shipping holds considerable contribution in economic and environmental impacts therefore it is important to study available options to reduce the environmental impact while the shipping industry keeps booming. A ship is selected in this work to access the available options and suggest the calculated alternative. A SIMULINK model is designed for the ferry ALMADENSE operating on Tagus River in this work and following objective are studied overall:

- Study possible alternative fuel technology.
- Model components of power system in SIMULINK for both hybrid and diesel ship. Simulate the model for a year of operation.
- Perform economic and environmental analysis for all the three cases.
- Calculate optimum size of hybrid system components.

II. LITERATURE REVIEW

Carbon emission contribution via shipping increased from 1.8% in 1996[5] to 2.9% in 2018[6]. Various studies have been conducted to assess possible implementation of technology for different size of ships and route including range of ship travel. Economic factor is proved to be most influential factor amongst all while studying the possible technology implementation[5]. Another key parameter for selection is played by the power required and distance intended to travel. This is due to the size and storage restrictions along with efficiencies, route predictability, present technology capabilities and up-front costs [7].

Although VLSFO is currently in use since new regulation enforcements in 2020 by IMO, there are a variety of alternative fuels that could be used as marine fuel such as LNG, methanol, LPG, ethanol, hydrogen, etc. Amongst these, LNG is the most studied alternative fuel currently. On the other hand, hydrogen provides a cleaner and efficient fuel, but it is limited to and short range shipping[5]. Table 1 represents the comparison between these fuels w.r.t. conventional MGO for their physical parameters[8]. These parameters important concerning their storage requirements.

Table 1. Physical properties of different fuel that could be used as alternative fuels for power generation[8].

Parameter	Density	LHV	Vol. energy density	Energy density
	[t/m^3]	[GJ/t]	[GJ/m^3]	[m^3/GJ]
MGO	0.835	42.7	35.7	1
LPG	0.49	46	22.6	1.58
H_2 @350 bar	0.023	120	2.8	12.78
H_2 liquid	0.071	120	8.52	4.18
Ammonia	0.61	18.6	11.4	3.17

In terms of transportation, liquid or gaseous hydrogen transportation is more efficient as compared to ammonia[9].

A hybrid combination of hydrogen and green ammonia is suggested by Gore, Ketan et. al. (2022) [10] for best environmental performance whereas, dual fuel engine with LNG for best NPV performance. These calculations also include carbon taxes, which is not applicable for the case study of ship selected in this thesis. Ammonia is also toxic for humans it could incur negative NPV due to its higher operation costs[10][11].

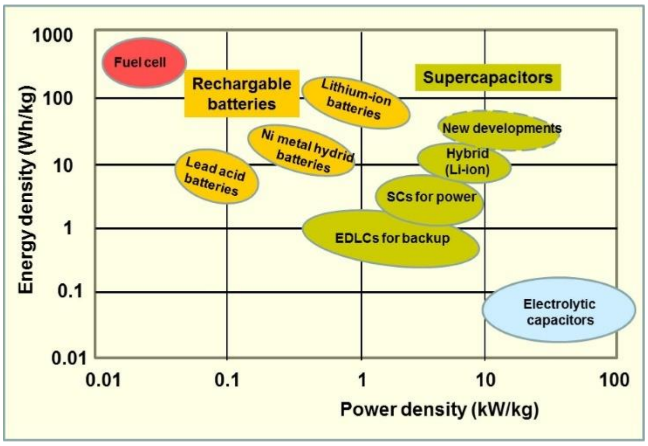


Figure 1. Ragone plot for various types of emerging green technologies to power the energy system based on their power and energy density.

Zuhang, Fu et. al. (2023) [12] concludes the dominance of compressed hydrogen for small and medium sized ships for short distances. On the other hand, Fuel cells have higher energy density but very low Power density. Whereas, Batteries have higher Power density which compliments the fuel cell as shown in Figure 1.

Electrochemical energy is harvested and converted into electrical energy in a Hydrogen Fuel Cell. Fundamentally, there are different types of Fuel Cell technology available today amongst which PEMFC (Proton Exchange Membrane Fuel Cell) is best suited for ships like ferries, boats and, fishing vessels as per Tjalve Svendsen, Head of Project for Alma Clean.

Study by Berkehan Inal, Omer et. al. (2020)[13] ranks fuel cell technologies on different parameters namely, Safety, Emissions, Efficiency, Cost, Lifetime, Power Output, Fuel Type and Size on a scale of 5. In conclusion, Diesel oil operated MCFC scores the highest, but it is not an environment friendly alternative as it uses fossil fuel. PEMFC scores the second highest therefore, these FCs are used in the case study in this work.

A considerable reduction of 65% Greenhouse gases has been analysed for a ferry in Denmark that uses hybrid hydrogen system by Peng Wu, et. al. [14]. But the study was conducted in 2019 with a fixed emissions generation of CO_2 per kWh electricity from grid. Also, Denmark’s energy grid mix is different from Portugal that affects the overall GWP for each case.

III. METHODOLOGY

This study focuses on the analysis of the ALMADENSE ferry, currently in operational service in Lisbon whose specifications are as per Table 2. Operating along the River Tagus, this diesel-powered ferry connects three key ports: Porto Brandão, Belém, and Trafaria, as illustrated in Figure 2.The vessel boasts a catamaran-style hull design renowned for its high efficiency, primarily attributed to minimized hull drag forces.

Table 2. Specifications of Ship "ALMADENSE", a RoPAX operating on the route Porto Brandão, Belém and Trafaria in Lisbon, Portugal.

	Value	Unit
Capacity	360 + 29	PAX + Vehicle
Length	47.5	m
Beam	16	m
Depth	3.65	m
Draft	2.2	M
Gross Tonnage	1479	
Total Engine Power	1268	kW

Ship starts its operation at 05:30 hrs and the last voyage finishes at 21:30 hrs when it arrives at Porto Brandão with a total voyage counting of 55.

Block coefficient of the ship has been calculated numerically using the Equation 1 given by C.D. Barras.

$$C_B = 1.2 - 2.378\,Fn \tag{1}$$

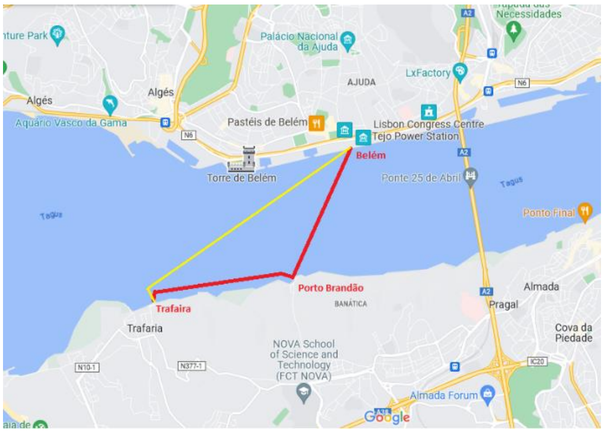


Figure 2. Ship's route in Tugus river (Red line indicates regular route that it follows whereas yellow line represents less frequently travelled route).

1. Case I – Hydrogen Hybrid System Modelling

To have an optimal design of energy system hybrid power system is designed in MATLAB SIMULINK with the principle as shown in Figure 3. The design simply works on the principle that in order to propel the ship at a certain velocity, it has to overcome all the resistance that it would encounter at that velocity which includes Hull resistance, wave resistance and air resistance. If the power supplied overcomes these resistances, ship will start moving at that speed.

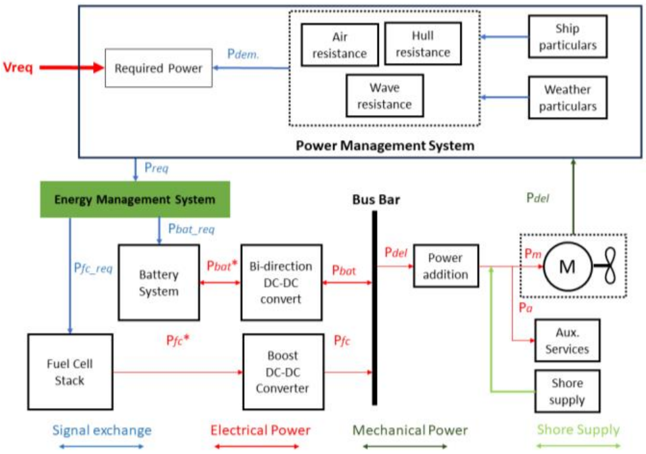


Figure 3. Hybrid Power system designed in MATLAB SIMULINK for RoPAX ship ALMADENSE operating on route Porto Brandão, Belém and Trafaria in Lisbon.

Velocity profile of the ship for an average day is used to simulate the designed model. Velocity demand profile is kept constant, but the months are varied affecting the power demand as forces depend on dynamic environmental conditions.

Modular Fuel Cell with a unit capacity of 200kW inspired by Ballard's FcWave module is used in the work. Output of Fuel cell module has varied voltage and current, to make the voltage constant, a DC-DC boost converted is used.

Simulation ran multiple time with varying Fuel Cell module number in order to decide the optimum number of Fuel Cell modules. One important deciding factor is the amount of hydrogen used during a year which affects its OPEX. To calculate the hydrogen used, hydrogen mass flow is also calculated during the simulation for every simulation step using Equation 2.

$$\dot{m}_{H_2} = \frac{{P_{fc}}^*}{\eta_{fc}\widehat{LHV}_{H_2}} \tag{2}$$

Where, ${P_{fc}}^*$ is the power delivered by fuel cell, η_{fc} is the FC efficiency for the corresponding load and $\widehat{LHV}_{H_2}$ is Lower Heating Value of Hydrogen. DC-DC boost converter stabilises the voltage output to 815V corresponding to the voltage requirements of DC propulsion motor. Motor used here is an ABB DC motor with Cat. No. 3BSM003050-XVJ having power rating of 1355 kW at 970 rpm. DC motor is used as these motors have high torque.

Apart from power requirement of propulsion, Power system in this work is also designed supply energy to ship's Auxiliary system. Auxiliary system includes all the necessary equipment like communication system, navigation system, fire management system, etc. and all the equipment required for comfortable movements of crew and passengers like air conditioning system, lighting, power ramps, etc. Study assumes fixes this power to a fixed value of 50kW. This power in port is supplied by battery power pack only.

As this is a hybrid power system, for lower number of fuel cell module simulation, remaining required power is drawn from battery pack for propulsion as well. This increases the size of battery. Apart from this, battery also provides interim power until fuel cell catches up. Equation 3 shows the total power available in bus bar.

$$(I_{FC} + I_{BATTERY})V = P_M \tag{3}$$

Power Management System (PMS)

Power Management System evaluates the real-time conditions acting on the vessel and their effects are compared with required power i.e., the desired velocity. After evaluation, as a result its output is net required power for the ferry to continue to propel at the set velocity and instructs the energy producers either to increase or decrease the power. This is done in simultaneous stages performing simultaneous calculations. PMS calculates the difference between the delivered power and the power opposing the propulsion ship due to environmental forces (namely Wave force, Wind force and, Air resistance).

PMS sense the difference in power and guide the energy providers either to increase or decrease power delivery. These decisions are as per Equations from 4 to 7.

$$P_{error}(t) = P_{ef}(t) - P_{del}(t) \qquad (4)$$

$$P_{req}{}^{*}(t) = K_p P_{error}(t) + K_i \int P_{error}(t) + K_d \frac{\Delta P_{error}(t)}{\Delta t} \qquad (5)$$

$$P_{ef}(t) = (F_{wave}(t) + F_{air}(t) + F_{hull}(t))v(t) \qquad (6)$$

$$P_{req}(t) = P_{req}{}^{*}(t) + P_{aux} \qquad (7)$$

$$0 \le P^{*}{}_{req}(t) - P_{aux} \le P_{\substack{max\\ motor}} \qquad (8)$$

Where, $P_{error}(t)$ is the generated difference, $P_{ef}(t)$ is total power opposing the propulsion, $P_{del}(t)$ is Power delivered by propulsion motor, $P_{req}{}^{*}(t)$ is power requirement except auxiliary power, K_p, K_d & K_i are controller constants, $F_{wave}(t), F_{air}(t)$ & $F_{hull}(t)$ are the forces exerted by external environmental conditions designed in SIMULINK as shown in Figure 4. $P_{req}(t)$ is the total required power estimated by PMS and, $v(t)$ is ship's current velocity. The power is limited by maximum motor power ($P_{\substack{max\\ motor}}$).

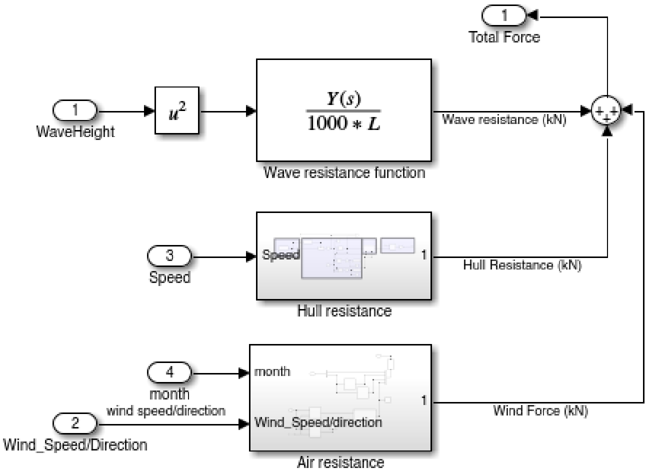


Figure 4. Individual calculation blocks of all the Forces acting on the ship's body namely in SIMULINK.

Wave resistance is calculated by the Equation 9 given by Kreitner[15]. Wave height in this equation is dynamic in nature and largely differs in every month of a year. For simulation in this work, average of each month is used for every second of ship's operational day.

$$\Delta F_{wave} = {0.64\xi(t)^2 B^2 C_B \sigma}/_{L} \qquad (9)$$

Where, $\xi(t)$ is wave height, σ is specific weight of water, L is length of ship and B corresponds to breadth of ship. Similarly, Air resistance is governed by Equation 10 where density of air varies each month of the year. This density depends on ambient temperature and pressure of air.

$$F_{air} = \frac{1}{2} C_d \rho_{air} A_{proj.} v^2{}_{attack} \qquad (10)$$

Where, C_d is the drag coefficient of the ship, this depends on the angle of attack of the incoming wind, ρ_{air} is density of air, $A_{proj.}$ is the projected sectional area of the ship for incoming wind that depends on the angle of incoming wind. Lastly, v_{attack} is the resultant velocity of incoming wind. This velocity is relative to actual wind speed & angle in addition to ship's speed and direction. This resultant wind velocity and direction is calculated as a vector product of both the velocities as represented in Figure 5.

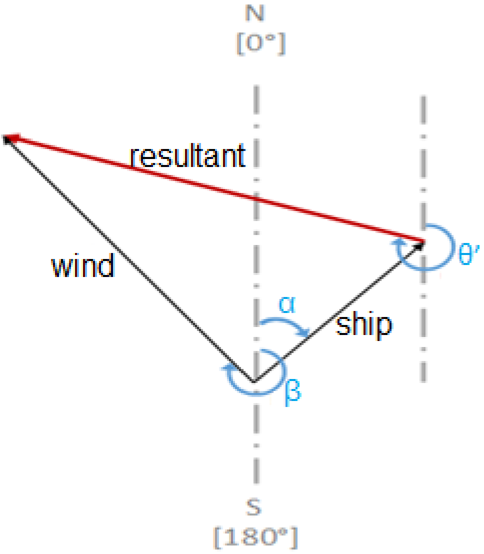


Figure 5. Vector representation that resultant vector will make w.r.t. North direction.

Lastly, Hull force or force exerted by water is calculated in the simulation. This force depends on the draft of the ship. More the draft, higher will be the hull force. Therefore, this force is calculated with varying draft simulated using a randomizer block of SIMULINK. A randomizer block generates a random signal for each voyage that changes the number of passengers and vehicles transported. Number of passengers & vehicles change the displacement of the ship and hence affect the draft according to the Equations from 11and 12. ANSYS Fluent software[16] is used to calculate the force exerted by moving mater for various drafts and the results are put into SIMULINK model as 2-D lookup table. During simulation, SIMULINK gives the force corresponding to the calculated draft.

$$T = T_{light\,weight} + T_{added} \qquad (11)$$

$$T'_{added} = \frac{W_{added}}{1000TPC}\,[cm] \qquad (12)$$

Where, T is the calculated draft, $T_{light\,weight}$ is light wight draft of the ship, T_{added} is the draft added due to added weight in meters, T'_{added} is added draft in centimetre, W_{added} is the total weight added and TPC is the parameter of ship represents to weight that is needed to change the draft by 1 cm.

Addition of all these forces results in total force, product of this total force and actual velocity of ship gives the opposing power $P_{ef}(t)$.

Energy Management System (EMS)

Energy Management System is responsible for the decision of distributing the power requirement between both the energy providers (Fuel cells and Battery system). To do that, firstly the system has to check if the vessel is in port or sailing as Fuel Cell System is not designed in this thesis to work on port and enters into ideal condition (air purging). EMS decides the energy distribution as shown in decision flow diagram shown in Figure 6. Fuel cell capacity depends on number of modules that changes for each simulation.

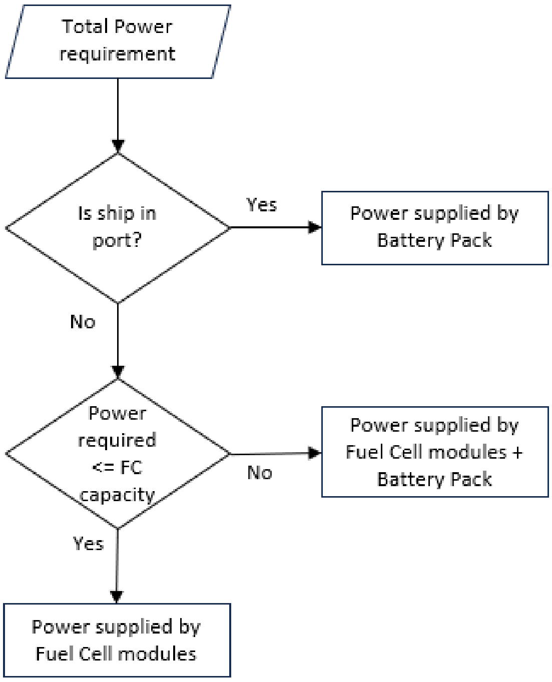


Figure 6. Energy Management System decision flow diagram principle for selected case.

2. Case II – Diesel Engine Modelling

It is important to compare the hybrid system with conventional Diesel Engine powered (current system) system in order to have a holistic analysis. To perform this analysis, diesel engine system is also modelled in SIMULINK and simulated under exactly same conditions. A MAN Diesel & Turbo 8L23/30A 4-stroke IMO Tier II engine[17] is considered with a power rating of 1280 kW for this work.

Also, as there is only one energy provider i.e., Diesel engine, Energy Management System is also omitted in this Case. Only thing left to calculate is the efficiency and the fuel consumption and both of these are inked together. To calculate fuel consumption, SFOC given in the manual[17] at reference conditions is used that gives the consumption as in Table 3.

Table 3. MAN 8L23/30A SFOC consumption at different engine load.

Load [%]	100	85	75	50	25
SFOC [g/kWh]	194	193	192	194	210

Manual also specifies that this SFOC changes with the change in ambient conditions (temperature and pressure) along with the charge air temperature. These conditions are measured, and a factor called “Fuel consumption factor” (γ) is calculated using Equations 13 and 14[17] which is than multiplied by the load SFOC.

$$\gamma = 1 + 0.0006(t_x - t_r) + 0.0004(t_{bax} - t_{bar}) + 0.07(p_r - p_x) \qquad (13)$$

$$SFOC_x = \gamma SFOC_r \qquad (14)$$

Where, $t_r, t_{bar}\,\&\,p_r$ are the reference ambient temperature, charge air temperature before cylinder and ambient air pressure respectively as given in the manufacturer's manual. Whereas $t_x, t_{bax}\,\&\,p_x$ are ambient temperature, charge air temperature before cylinder and ambient air pressure respectively corresponding to the conditions under simulation. Lastly, $SFOC_r$ is reference SFOC as given in Table 3 and $SFOC_x$ is the calculated SFOC engine under the simulated ambient conditions.

Schematic diagram of the designed SIMULINK model made is based on the principle as shown in Figure 7. Power Management System of Case II – Diesel Engine Modelling remains the same as of Case I – Hydrogen Hybrid Modelling as there is no change in location of operation or physical properties of the ship. Remaining modelling is majorly based on SFOC of the engine under consideration.

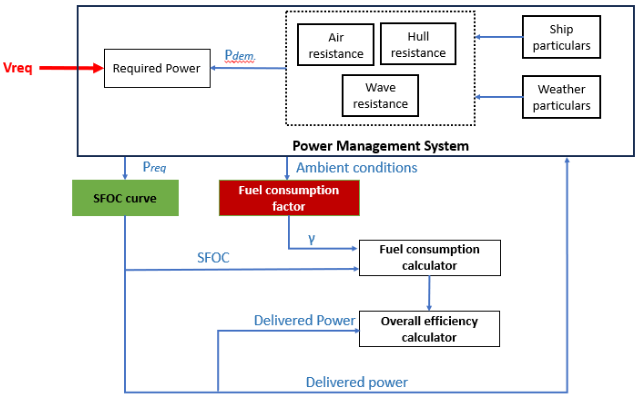


Figure 7. Case 2 principle schematic diagram representing the flow of signals and values required for the simulation.

In order to access the economic and technological development to compare Case I and Case II, amount of diesel fuel used is required. Diesel flow rate is calculated using the power output and SFOC together using Equation 15.

$$\dot{m}_{fuel} = P_{del}(t)\,SFOC_x(t) \qquad (15)$$

Overall efficiency of diesel engine in this case is calculated by dividing the power delivered by the engine by the power potential of fuel used to deliver that power. This is designed using the Equations 16 and 17.

$$P_{fuel}(t) = \dot{m}_{fuel}\widehat{LHV_{FO}}\,\frac{60 \times 60}{3.6 \times 1000} \qquad (16)$$

$$\eta_{DE} = {P_{del}(t)}\Big/{P_{fuel}(t)} \qquad (17)$$

IV. INITIAL RESULTS

Case I – Hydrogen Hybrid System Results

Energy distribution amongst the fuel cell modules and battery largely depends on the size of the Fuel cell capacity. Battery acts as a buffer until when Fuel cell system takes over or if Fuel cell does not have the capacity to reach the power required.

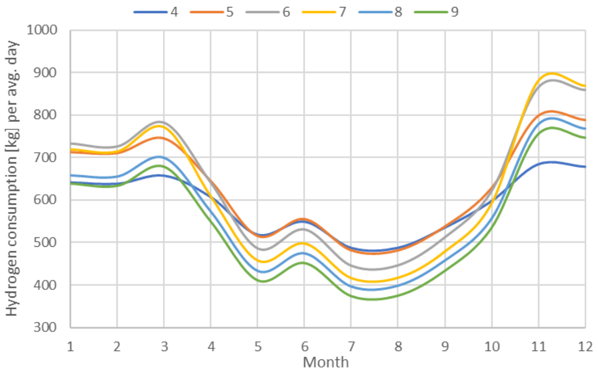


Figure 8. Hydrogen consumption in kg for avg. operating day of the month throughout the year for varying Fuel cell (200kW unity) module number.

Hydrogen consumption over a year follows the "U" shaped characteristic as seen in Figure 8. This is due to the decreased external forces in summers. Due to elevated temperature, density of air and water is low, with lower wave heights. Hydrogen consumption reaches it peak in the month of November. Figure 8 also represent graph for different fuel cell modules showing difference between the consumption.

Total yearly consumption increases with the increase in number of FC modules until 6 and then experiences a dip as number increases as seen in Table 4. This is because as the number of FC modules increases, load on each module decreases. Fuel cells have higher electrical efficiency with low loads.

Table 4. Hydrogen fuel consumption per year for different FC module configuration in kg.

FC module no.	H_2 consumed [kg]
4	215,279
5	231,020
6	232,470
7	225,565
8	208,157
9	199,774

Simulation also help in deciding the capacity of the battery installed. Power required at every instance in all the fuel cell modules is same, therefore, for example, if 1000 kW power is required at a given time but fuel cell modules has the capacity of delivering 800 kW only (in case of 4 FC modules), remaining power will be compensated by battery. This results in total energy delivered by battery in a year will be higher for lower FC module as shown in Table 5.

With the increase in fuel cell modules, energy consumption through battery decreases. This is simply because the required energy is primarily delivered through fuel cells. But Table 5 shows that after 7 modules, consumption does not decrease further. Reason behind it is that after 7 modules, fuel cells have enough to match the required power and battery is only essential while in port.

Table 5. Energy consumed by battery in a year for varying Fuel cell module configuration.

FC module no.	Electricity consumed [MWhe]
4	676.06
5	388.70
6	217.50
7	131.58
8	130.09
9	130.09

Case II – Diesel Engine Results

After simulation, Case II also follows the similar “U” shaped fuel consumption characteristic. This is also be seen in the engine efficiency for different months. Maximum fuel consumption is in the month of November similar to the results of Case I. In total, diesel engine consumes 472,136 kg diesel in a year.

V. MODULE SELECTION AND ECONOMIC STUDY

Apart from all the technical analysis, economic study is equally important in order to make the project selection viable for the investors. Also, according to a study as discussed in Section II. by Moshiul et. al. [5], economic factor influences the technology selection the most. Therefore, FC module with the maximum return has been selected. Economic study is based on various market parameters. Parameters like inflation, discount rate, etc. affects the returns of a project. These parameters are calculated assumptions as shown in Table 6.

Table 6. Market parameter for economic analysis

Parameter	**Value**
Expected inflation rate (i)	0.88%
Interest (I)	5.0%
Taxes	21.0%
Loan Tenure	30 years
Payment Receiving Period (Days)	30 days
Payment Sending Period (Days)	44 days
Discount rate[18]	6.08%

Linear depreciation of equipment is considered in this work as shown in Table 7. To calculate lifetime returns of a project, components lifetime, CAPEX and OPEX are required, Table 7 show these values for all the components used in this work.

Table 7. Equipment life in years, CAPEX and OPEX[19] [20] [21] [22] [23] [24] [25]

Equipment	Life	CAPEX	OPEX
Ship (diesel engine)	30	7,000,000 €	69,068 €/yr
Engine	30	318.18 €/kW	61,948.73 €/yr
Fuel cell	30	909.1 €/kW	4.73 €/(kw-yr)
Hydrogen storage	30	656.36 €/kg-H_2	9.1 €/(kw-yr)
DC-DC converter	30	181.82 €/kW	3.0 €/(kw-yr)
Battery	10	120.0 €/kWh	0.45 €/(kw-yr)
Propulsion motor	30	122.73 €/kW	1.23 €/(kw-yr)

Net Income of a project depends on revenues generated and expenses. For ALMADENSE, revenues are generated by ticket sales of vehicles and passenger along with some complimentary revenues [23]. Expenses like crew salary[23], ship maintenance costs and fuel charges affects the Net Income of a year. This in-turn affects the project’s return.

Diesel & Fuel prices are constantly fluctuating in the market and therefore for prices before 2022 has been sourced from TTSL (ship operator) reports. For prices beyond 2021, prices are assumed and calculated based on forecasts made by DNV in their Maritime Forecast to 2050 as shown in Figure 9.

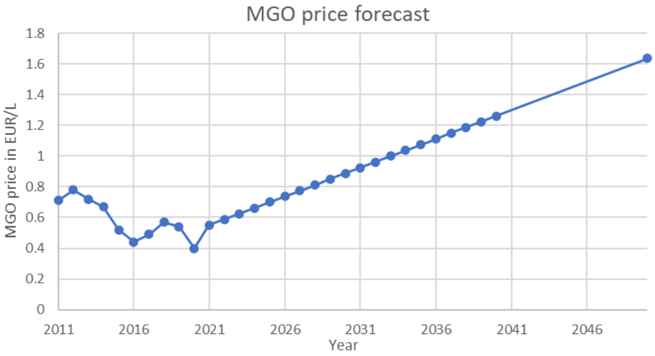


Figure 9. MGO price forecast from 2011 to 2050 in Euro per Liter made by DNV.

Green hydrogen is used as it is accepted to be the most environmentally friendly technology of producing hydrogen. As the ship operates in Portugal, prices considered are also associated with Portuguese costs(see Figure 10) as per the research results of PwC[26] until the year 2050. For years beyond 2050, linear forecast is done.

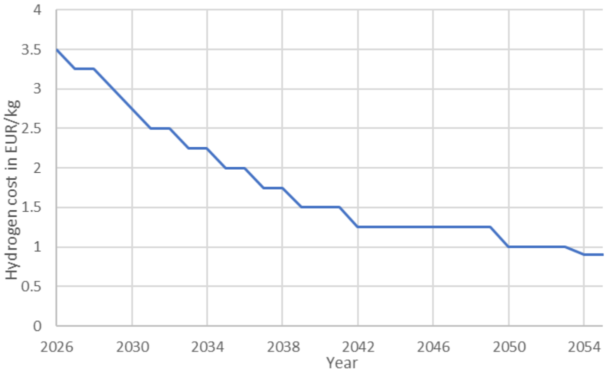


Figure 10. Green hydrogen price forecast from 2026 to 2055 in EUR/kg for Portugal

Electricity required in this work is used to re-charge the battery while in port. Batteries will be charged during the off-time operation i.e., during the nights and this electricity is drawn from the grid. Since the requirement of electricity begins in the year 2026, it necessitates forecasts. In this work, forecasts prepared by Energy Brainpool in their research for average baseload price for EU27 countries are considered[27]. Beyond 2050, the last trend is followed and continued until 2055 (see Figure 11).

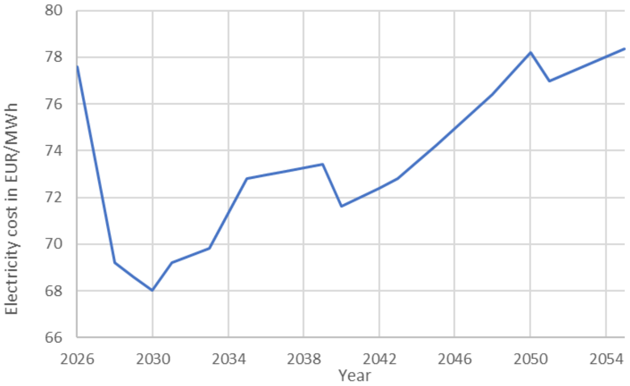


Figure 11. Average electricity prices in €/MWh from 2022 to 2050 with liner forecasts until 2055.

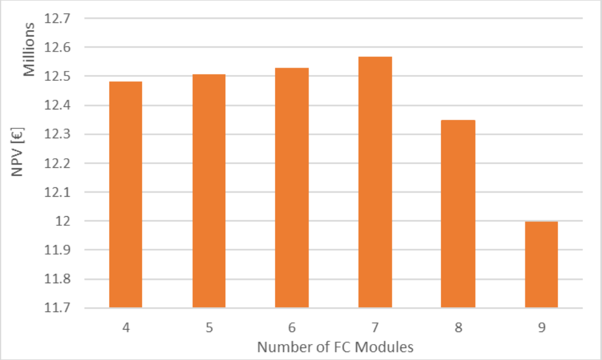
Annual Profit & Loss Accounts, Annual Balance Sheet and Statement cash flows are generated for all the three case scenarios for the ship's lifetime of 30 years. Fuel expenses after the calculations shows the one of the key factors that affects the economic analysis apart from CAPEX and OPEX.

For Model scenario 2 and 3 that uses Hybrid FC System, calculations are done with changing FC modules. To select the economically viable solution, optimum number of modules are selected with a balanced approach of IRR and NPV. These two are considered as key performance indicators and are calculated using Equation 18 and 19.

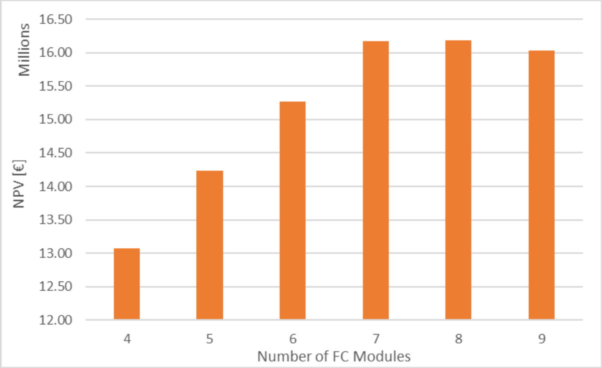
$$NPV = \sum_{a=1}^{n} \frac{F_{VAR}(a)}{(1+d)^a} - Total\ Investment \qquad (18)$$

$$0 = NPV = \sum_{a=1}^{n} \frac{F_{VAR}(a)}{(1+IRR)^a} - Total\ Investment \qquad (19)$$

Where, F_{VAR} is financial Cah Flow for the year a, d is discount rate, NPV is Net Present Value and IRR is Internal Rate of Return of a project.



(a)



(b)

Figure 12. (a) Model 2 NPV of business over its lifetime for different configurations of FC Modules; (b) Model 3 NPV of business over its lifetime for different configurations of FC Modules

Figure 12 shows the NPV of Model 2 and 3, max. NPV for Model 2 is with 7 FC modules whereas, for Model 3, 8 FC modules achieve higher NPV with very small margin. Although, 8 FC modules have edge but there is only 0.03 % increase in NPV w.r.t. 7 FC modules. On the other hand, investment increases by 2.35% w.r.t. 7 module configuration.

For IRR, Similar conclusion is resulted i.e., 7 FC module configuration. Change in IRR is also similar as shown in Figure 13.

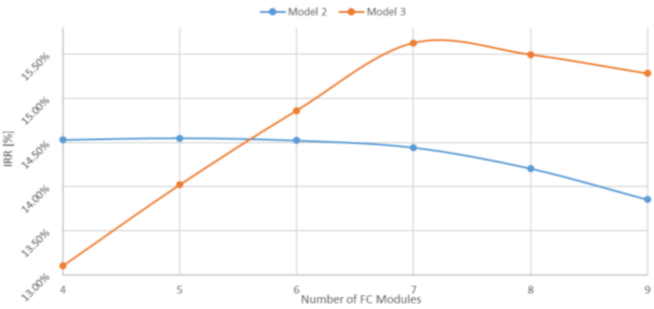


Figure 13. Model 2 & 3 IRR for different Fuel cell configurations used to select appropriate configuration.

VI. SELECTED CONFIGURATION RESULTS

With the simulation results, it is validated that for the instances where ship cannot reach the desired velocity due to power limitations as external forces dominates, velocity limits to the point where the maximum power is achieved for the given conditions.

Hydrogen storage tank is based on the value obtained by simulation and is designed for the highest consumption. A total of 880.3 kg-H_2 is consumed during an average day in November, making it the highest hydrogen consumption in a year. Tank is oversized by 20% totalling to 1,100 kg tank. Figure 14 shows the consumption of Hydrogen from the starting of its operation day (5:31 hrs) until the end (21:59 hrs).

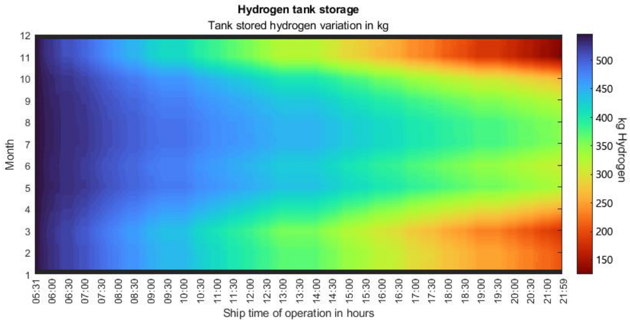


Figure 14. Hydrogen tank variation contour graph for average operation day of each month of the year.

Battery capacity selection is also done in the similar way and the highest being at 369.8 kWh. Battery capacity for this is using the Equation 20 as below:

$$C_{BAT} = \frac{E_{BAT_{CON}}}{\eta_b k_{DoD}} = 770.58\, kWh \qquad (20)$$

Where, C_{BAT} is installed battery capacity, $E_{BAT_{CON}}$ is energy consumed (369.8 kWh), k_{DoD} is assumed DoD of battery (50%) and η_b is assumed total battery efficiency. Battery in this case is designed to operate between 90% and 40% of its total capacity. This increases the lifetime of a battery and keeps the battery healthy for longer period of time. Figure 15 shows the variation in Battery energy during its operation day for an average day of month in a year.

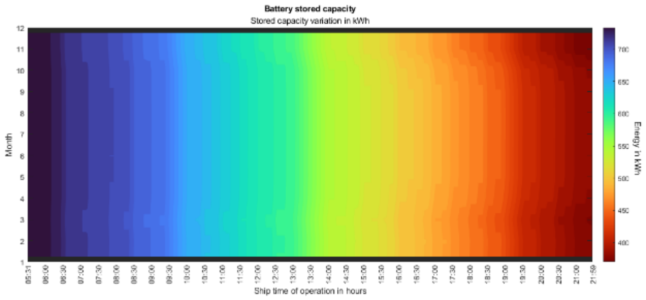


Figure 15. Battery capacity variation contour graph for average operation day of each month of the year.

Environmental pollution

Environmental protection is the main theme of this work. Combustion of each ton of oil in the engine produces 3.206 tons of CO_2. Whereas, fuel cells do not produce any emission while in operation. Emissions generated by the grid electricity to charge the battery depends on the energy mix of the grid. More than 67% of electricity came from renewable sources[28] between January 1 and September 30, 2023

Portugal's Prime Minister, António Costa, has made a firm commitment to achieve net-zero grid electricity carbon emissions by 2045. Therefore, as a result, a linear reduction in carbon emissions from 2020 to 2045 is employed for emission calculations (see Figure 16) in this work.

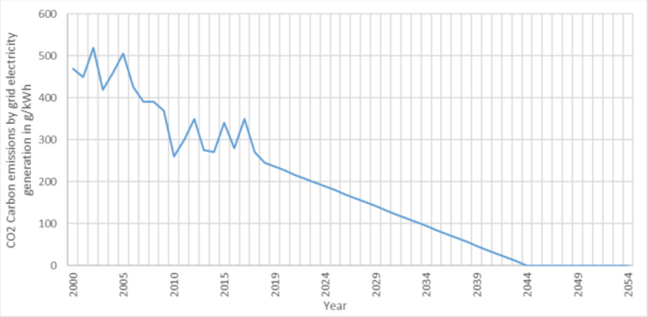


Figure 16. Carbon emissions via grid in Portugal from 2000 until 2055 includes historical data (2000-2019) and predictions (2020-2055)

Through Simulation of Case 1 and Case 2 for Model 1, 2 & 3, fuel consumptions were recorded for every month of a year. To compare the lifetime emissions of each Model, yearly emissions are considered, and models are compared by their lifetime emissions as shown in Table 8. Model 3 evidently reduced emissions to almost 97% whereas, Model 2 reduced emissions by almost 47% as compared to Model 1.

Table 8. CO_2 emission results of all models considered in this work over the lifetime of their operation in tons.

	Model 1	**Model 2**	**Model 3**
CO_2 emissions [tons]	45,410	23,947	1,310

VII. CONCLUSION & FUTURE WORK

Simulation performance shows the ability of hybrid fuel cell model to reduce carbon emissions to only 3% for Model 3 and 53% for Model 2 as compared with Model 1. Economically, CAPEX of battery is one of the key influencing factor as it is a recurring investment where it contributes to 3% and 7.7% for Model 2 and Model 3 respectively apart from fuel costs. Upfront FC Hybrid system cost along with hydrogen fuel and electricity costs must plunge down to take-over conventional engines. Increase in FC modules lead to an increase in capital cost but, this cost factor alone do not solely dictate the selection of a technology. Cost of hydrogen as a fuel decrease with the increase in FC modules. This affects configuration selection, this cost denote around 61% of all expenses. With the economic selection criteria 7 FC modules with a battery size of 770kWh for Model 3 perform the best with an IRR of 15.63% and NPV of 16.1 M€. On the other hand, Model 2 selection makes more sense as replacing the relatively new ship is a difficult decision.

Future possible work includes enhanced calculations to match the EEXI requirements, inclusion of degradation of equipment involved over the period of time in the work and analysis of possible on-board renewable re-charging facilities. Designed model can also be adopted to analyse different ships operating in different locations with changing only few certain parameters and blocks.

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